ATOMIC LAYER DEPOSITION OF CONFORMAL DIELECTRIC AND PROTECTIVE COATINGS FOR RELEASED MICRO-ELECTROMECHANICAL DEVICES

Nils Hoivik, Jeffrey Elam*, Ryan Linderman, Victor M. Bright, Steven George* and Y.C. Lee

NSF Center for Advanced Manufacturing and Packaging of Microwave, Optical and Digital Electronics. Department of Mechanical Engineering,

* Department of Chemistry and Biochemistry

University of Colorado at Boulder, CO 80309, USA

Abstract – **This paper describes a novel fabrication approach using Atomic Layer Deposition (ALD) of dielectric materials to protect and coat released MEMS devices. The nature of ALD film ensures coverage on all sides of a released MEMS device and is done at a relatively low temperature (down to 150°C). The ALD film thickness can be precisely controlled as each reaction cycle deposits approximately one monolayer of atoms. To demonstrate the concept of conformal layer deposition, alumina (Al_2O_3) was deposited onto released MEMS devices prior to electrostatic testing. Curvature and increase in beam stiffness for coated MEMS devices were investigated.**

I. INTRODUCTION

This paper describes a novel fabrication approach using Atomic Layer Deposition (ALD) of dielectric materials to protect and coat released MEMS devices. ALD is a coating process capable of depositing ultra-thin, conformal films of a variety of materials with Ångstrom-level thickness control. The ALD process relies on a binary reaction sequence of self-limiting chemical reactions with one atomic layer deposited during each cycle, thus extremely well controlled film thickness can be obtained [1].

For many MEMS devices there is a need for a conformal layer of material to prevent electrical shorting, isolate interactions with other materials or improving wear resistance. To demonstrate the concept, a conformal layer of alumina (Al_2O_3), an excellent RF dielectric, was deposited onto released MEMS devices in order to prevent shorting between conducting parts. Thin, conformal coatings of harder materials are expected to protect moving parts from wear and thereby increasing lifetime of the devices. Also, the problems of stiction of suspended MEMS structures may be eliminated by the use of thin, anti-stiction coatings using this technique. For adhesion caused by charge build-up, conductive coatings with controlled resistance can be deposited.

Surface coatings have previously been deposited on released MEMS structures using chemical vapor deposition (CVD) and self-assembling monolayer (SAM) techniques [2,3]. In this paper the results of using ALD alumina is described. A major advantage of ALD compared to other techniques is the unique conformality of the deposited films. The ALD films will cover all sides of a released MEMS device including bottom surfaces, such as underneath cantilever beams (Figure 1), which significantly improves the performance of electrostatically actuated devices. Another advantage of this process is that it can be carried out at temperatures down to 150°C – significantly cooler than typical CVD temperatures. This allows for the coating of composite devices made from materials such as poly-silicon and gold as in the MUMPS process without the risk of damaging the individual layers in the MEMS device. In addition, polymer based MEMS devices could also be coated at low temperatures. The deposition technique is compatible with integrated circuit devices as well as thermally sensitive packaged systems. Lastly, ALD may allow the coating of MEMS devices with biocompatible films in order to make the devices in vivo capable. For example biocompatible films, such as ALD TiO_2 films, could be deposited in order to isolate the charge from electrostatic fluidic actuators such as resonant micro fans [4].

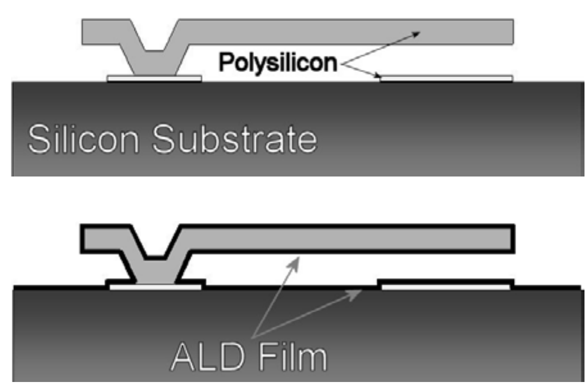

Figure 1: Illustration of released cantilever beam and ALD film growth.

II. Deposition Process

A. Description of ALD deposition

Atomic layer deposition (ALD) is a thin film growth technique allowing atomic-scale thickness control. ALD utilizes a binary reaction sequence of self-limiting chemical reactions between gas phase precursor molecules and a solid surface [1]. Films deposited by ALD are extremely smooth, pinhole-free and conformal to the underlying substrate surface. This conformality enabled successful coating of powders, nanoporous membranes and high aspect ratio trench structures [5]. Furthermore, ALD is a low temperature process enabling deposition on thermally sensitive materials and established techniques exist for growing a variety of materials including oxides, nitrides and metals.

Figure 1 illustrates the atomic layer deposition process. Reaction A deposits a monolayer of chemisorbed species on the surface. Because the resulting surface is inert to precursor A, further exposure generates no additional growth. Next, precursor B is introduced. This molecule reacts with the product surface from the A reaction in a self-passivating manner. Consequently, the B reaction terminates after the completion of one atomic layer. If reaction B regenerates the initial surface, then the two reactions can be repeated in an ABAB… binary sequence to deposit a film of predetermined thickness.

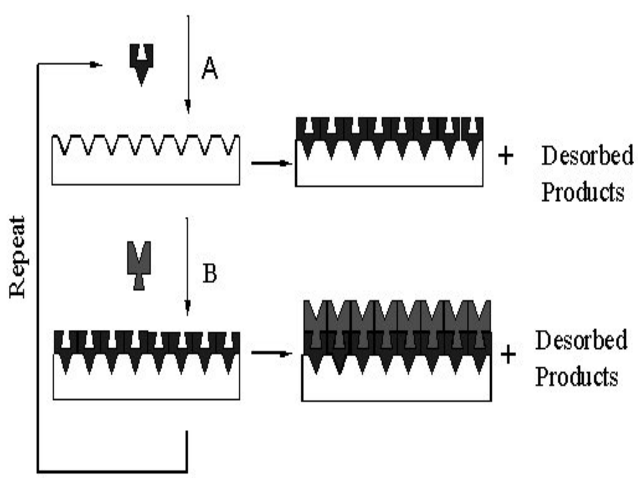

Figure 2: Description of ALD process.

One example of this process is the atomic layer deposition of Al_2O_3 consisting of the following binary reaction sequence in which the asterisks designate the surface species:

A) $Al\text{-}OH^* + Al(CH_3)_3 \rightarrow Al\text{-}O\text{-}Al(CH_3)_2^* + CH_4$

B) $Al\text{-}CH_3^* + H_2O \rightarrow Al\text{-}OH^* + CH_4$

In reaction A, the $Al(CH_3)_3$ reacts with the surface hydroxyl groups to deposit a new monolayer of aluminum atoms terminated by methyl groups. In reaction B, the methylated surface reacts with H_2O vapor, thereby replacing the methyl groups with hydroxyl groups. CH_4 is liberated in both the A and B reactions. The net result of one AB cycle is the deposition of one monolayer of Al_2O_3 onto the surface.

Figure 2 presents ellipsometry and stylus profilometry thickness measurements for ALD Al_2O_3 films deposited using alternating $Al(CH_3)_3$, H_2O exposures. The ALD Al_2O_3 film growth is extremely linear with the number of AB cycles performed and the growth rate is 1.29 Å/cycle. Inspection of the ALD films on planar surfaces using atomic force microscopy has revealed pinhole free coatings with nearly the same surface roughness as the underlying silicon substrate.

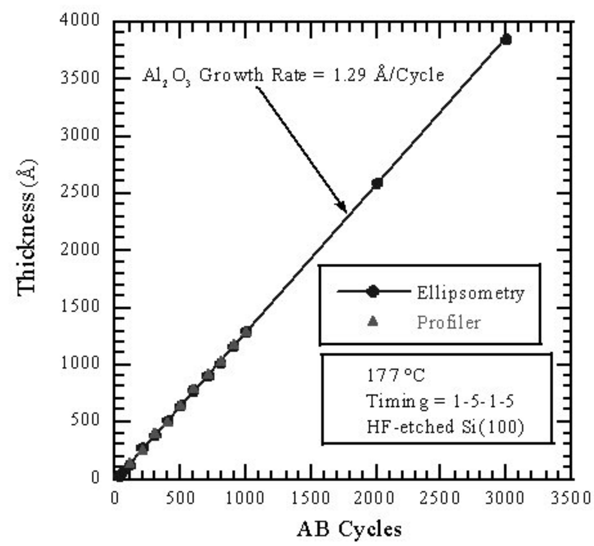

Figure 3: Thickness measurement of ALD deposited alumina film.

B. Description of MEMS test devices

Currently, several MEMS devices have been coated with alumina including released micro cantilever test structures, flip-chip variable RF capacitors and resonant micro fans used for fluidic transport mixing and particle separation. All of the above-mentioned MEMS devices were constructed using the MUMPS technology provided by Cronos Corporation which includes three layers of polysilicon, two layers of oxide and one layer of gold [6]. All MEMS devices were released from the sacrificial oxide in a HF acid etch. Following the HF release the devices were dried in a CO_2 supercritical drying chamber. No other pre-treatment was performed on the MEMS devices prior to ALD coating.

As test devices, basic cantilever beams and resonant micro fans (Figure 3 and 4) were coated with ALD deposited alumina of various thicknesses. The length of the cantilever beams ranged from 150 to 300 µm with a constant width of 60 µm. For electrostatic testing of the cantilever beams, the alumina layer thickness of 20, 40 and 60nm were chosen, whereas the resonant micro fans were coated with an 80nm thick alumina layer. The ALD deposition was performed at a temperature of 177°C for all devices with no further processing required.

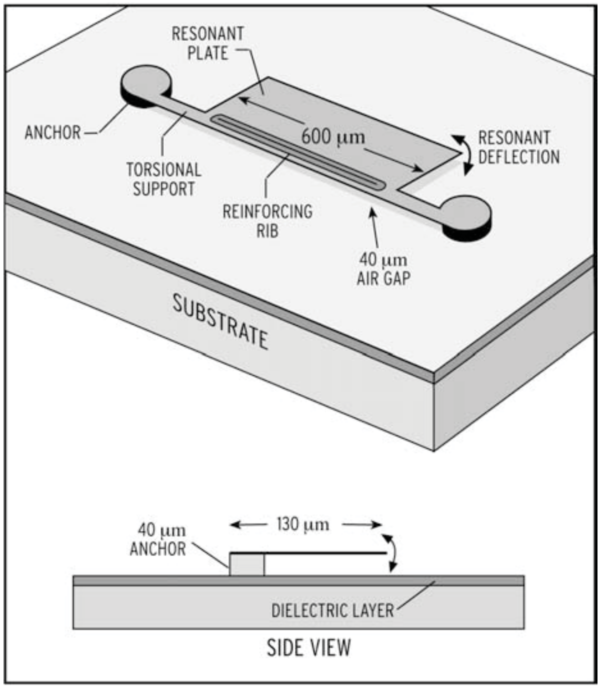

Figure 4: Diagram of torsionally supported plate resonator. Polysilicon plate and support thickness is 1.5 microns.

III. RESULTS AND DISCUSSION

A. SEM and FIB imaging of ALD deposited layer

After coating the cantilever beams with alumina, the 60nm sample was further investigated using Focused Ion Beam (FIB) and Scanning Electron Microscopy (SEM) techniques. One of the cantilever beams was cut using the FIB and close up pictures of the alumina layers were taken using SEM. The FIB cuts directly down through the cantilever beam, electrode below and into silicon substrate. Figure 5 illustrates the cantilever beam and section where the SEM image was taken. The SEM depicts the suspended right corner of the tip on the beam. The part of the polysilicon beam that appears as a waterfall is an artifact from the FIB milling process. As the individual layers of the device are "melted" away by the ion beam, the material that does not get evaporated leaves an overhang at the edge. Using a polishing cut to remove the residue and overhang, one can see the individual layers in the cut out section much clearer. Alumina is a dielectric and thus discharges electrons during SEM investigation. Consequently, the white lines underneath the released cantilever beam indicate a uniform layer of alumina.

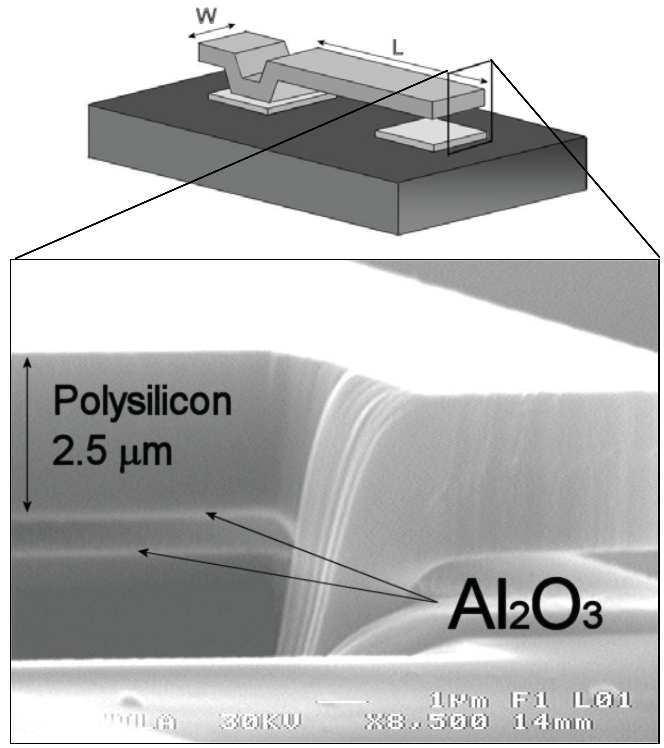

Figure 5: Illustration of beam and FIB cut section depicting deposited alumina layer.

Since the ALD alumina is deposited uniformly onto the released MEMS device, both on top and bottom, no change in device curvature should be observed. However, preliminary interferometric measurements of coated vs. uncoated cantilever beams indicates that the radius of curvature varied for coated samples when compared to uncoated ones. The radius of curvature was measured on the 60 by 250 µm cantilever beam, where the value changed from 180 mm to 100 mm with the presence of a 60nm thick layer of alumina.

B. Electrostatic Actuation

The uncoated polysilicon beams tested stuck down when an electrostatic load deflected the beams sufficiently to make a short by touching the opposing electrode. After depositing of alumina coating no shorting was observed and the beams could be repeatedly actuated beyond the snap-through voltage (100,000 contact cycles observed during basic electrostatic tests). The pull-in voltage of the cantilever beams did increase slightly as the thickness of alumina coating was varied (see Figure 6). For the 60nm coated cantilever beams, the increase in pull-in voltage ranged from 30 to 50%. This increase is expected since the alumina layer will increase the beam stiffness and affect the pull-in voltage. Increase in beam stiffness is generally tolerable since it can easily be compensated by modification of design.

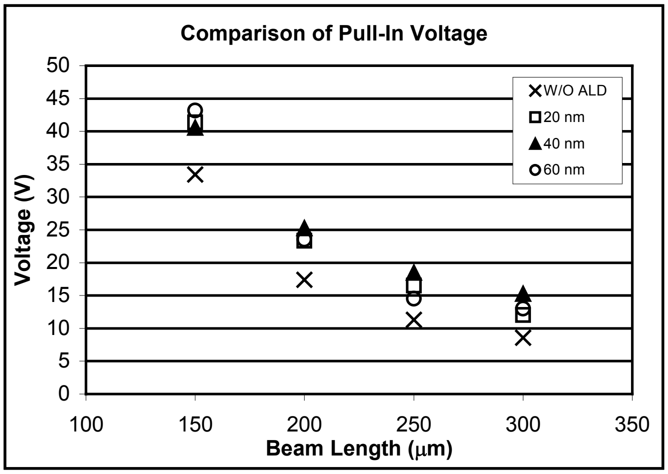

Figure 6: Pull-In voltage of MEMS cantilever beams with various ALD thickness.

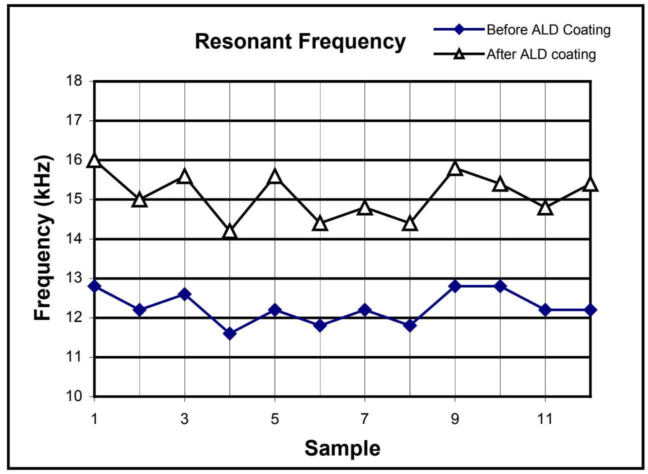

Figure 7: Comparison of resonant frequency for micro-resonators before and after alumina ALD coating.

A study of the change in resonant frequency of the polysilicon resonant micro fans (Figure 4) coated with 80nm of alumina has also been performed. The results are presented in Figure 7. The resonant frequency increase is largely due to added stiffness in the torsional supports with little effect from any added mass on the plate. With the deposition of an appropriate biocompatible material, to prevent electrolysis and other electro chemical interactions, the micro resonant fans could be used for lab-on-a-chip or other bio-analysis applications.

IV. SUMMARY

This paper describes a novel fabrication approach of protecting released MEMS devices using Atomic Layer Deposition (ALD). The ALD film thickness can be precisely controlled and various deposition materials, such as alumina (Al_2O_3) can be uniformly applied to structures at a relatively low temperature (177 ^oC for Al_2O_3). Testing of MEMS devices indicates a very uniform coating of released devices. ALD coating of electrostatically driven cantilever beams prevented shorting and failure when activated beyond pull-in voltage. However a slight increase in beam stiffness was observed, due to the added strength of the coating. After ALD coating of resonant micro fans the resonant frequency increased due to added stiffness in torsional supports. Interferometric measurements indicate a small increase in radius of curvature for coated MEMS devices. The change in stiffness could easily be accounted for by slight modifications in component design.

V. ACKNOWLEDGEMENTS

This research and development was partially funded by DARPA: FAME Grant # F33615-98-C-5429. The authors would like to thank Danelle M. Tanner and Alejandro A. Pimentel at SANDIA National Labs at Albuquerque as well as David Alchenberger at W. M. Keck Optical Measurement Laboratory JILA, University of Colorado for aiding in photo microscopy of the samples.

REFERENCES

[1] "Surface Chemistry for Atomic Layer Growth", S. M. George, A. W. Ott and J. W. Klaus, Journal of Physical Chemistry (100) 1996, pp. 13121-13131.

[2] "Novel Low-Temperature CVD Process for Silicon Carbide MEMS", C.R. Stoldt, C Carraro, W.R. Ashurst, M.C. Fritz, D. Gao and R. Maboydian. Transducers'01 Digest, Munich Germany, pp 984-987

[3] "Self-assembled monolayers as anti-stiction coatings for MEMS: characteristics and recent developments" R. Maboudian, W. R. Ashursts, C. Carraro. Sensors and Actuators 82 (2000), pp 219-223.

[4] "The Resonant Micro Fan for Fluidic Transport, Mixing and Particle Filtering", R. Linderman, S. Sett and V. M. Bright, Proceedings of 2001 ASME. International Mechanical Engineering Congress and Exposition, Nov. 11-16, 2001, New York, NY USA.

[5] M. Ritala, M. Leskela, J. Dekker, C. Mutsaers, P.J. Soininen, and J. Skarp, Chemical Vapor Deposition, 5, (1999), 7-9.

[6] http://www.memsrus.com